HOW TO EVALUATE ALTERNATIVE DESIGNS BASED ON FIRE MODELING

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How to Evaluate Alternative Designs Based on Fire Modeling

How does a code official know whether an alternative design analysis is credible? Read on to find out . . .

These days, fire models are being widely used to help code officials determine whether alternative design analyses—such as those sometimes used in unique buildings or large projects—provide protection equivalent to that prescribed by existing building codes. However, many code officials faced with the application of a new engineering method in a high-profile project are uncomfortable if there is no independent verification that such analyses have been done properly.

That's why I wrote this article: to provide some guidelines that you can use to determine whether an alternative design analysis is credible. My comments are based on my own experience in assessing alternative design analyses for several high-profile projects and on my experience developing and applying fire models.

As an example, let's calculate the equivalency of a fire model to code provisions for the safe evacuation of building occupants. To ensure a valid result, several steps are required. First, you have to establish the acceptance criteria. You must then select the appropriate fire models and the design fire or fires. Finally, you must perform an evacuation calculation, account for uncertainty, and do a reality check.

Establishing the acceptance criteria

Because the primary purpose of many fire safety code requirements is to allow all occupants to leave a building safely, the vast majority of alternative design calculations involve egress analysis. This is typically done in two parts: First, you estimate the fire development and smoke filling time, which establishes the time available for safe egress, then you estimate the evacuation time needed by the maximum population expected in the exposed area. If the time available is greater than the time needed, the occupants are safe, and the building complies with the intent of the code.

The first part of the calculation is most often based on a conservative assumption, which states that escape is no longer possible once the smoke layer has filled down to head height, which is usually 1.5 meters or 5 feet from the floor (see Figure 1). In fact, some models can predict the increase in smoke density within the layers, both upper and lower, so that a specified limit of either smoke level or visibility distance can be used. There will not be much difference between these two factors if the conservative assumption is used, except in slowly developing fires, which are not normally used as design fires, or in situations where little buoyant layering is expected.

There are also some situations in which egress is not the objective—or at least, not the only one. In some industrial occupancies, such as nuclear power or chemical processing plants, the consequences to public safety of a fire lead to code requirements intended to prevent exposure of critical systems or processes. In occupancies in which people have limited mobility, such as health care, correctional, and some board and care institutions, the codes may envision "protection in place." In both of these instances, only the filling time calculation is needed, and it may be desirable to estimate how susceptible the critical equipment or people are to damage. Again, models that do this are available.

Fire models

A recent survey documented 62 fire models and calculation methods that could be used, so you need to determine which are appropriate to a given situation and which are not.[1] To make this decision, you need a thorough understanding of the assumptions and limitations of the individual model or calculation and how they relate to the situation being assessed.

Fire is a dynamic process of interacting physics and chemistry, so predicting what is likely to happen under a given set of circumstances is daunting. The simplest of the predictive methods are the algebraic equations. Often developed wholly or in part from correlations to experimental data, they represent, at best, estimates with significant uncertainty. Yet, under the right circumstances, they provide useful results, especially when used to help set up a more complex model.[2,3]

Where public safety is at stake, it is too risky to rely solely on such estimation techniques for the fire development and smoke filling calculation. In these cases, only fire models should be used. Single-room models are appropriate where the fire is limited to a single, freely connected space. Where there is more than one space, and especially where they are on more than one floor, multiple-compartment models should be used because the interconnected spaces interact to influence fire development and flows.

Many single-compartment models assume that the lower layer remains at ambient conditions.[4] Since there is little mixing between layers in a room unless there are mechanical systems, these models are appropriate (see Figure 2). However, significant mixing can occur in doorways, so multiple-compartment models that allow the lower layer to be contaminated by energy and mass should be used.

The model should also include the limitation of burning by available oxygen. This straightforward calculation, based on the oxygen consumption principal, is crucial to accurately predicting ventilation-controlled burning. It is equally important that multiple-compartment models track unburned fuel and allow it to burn when it encounters enough oxygen and a temperature that is high enough. Without these features, the model concentrates combustion in the room of origin, overpredicting conditions there and underpredicting conditions in other spaces.

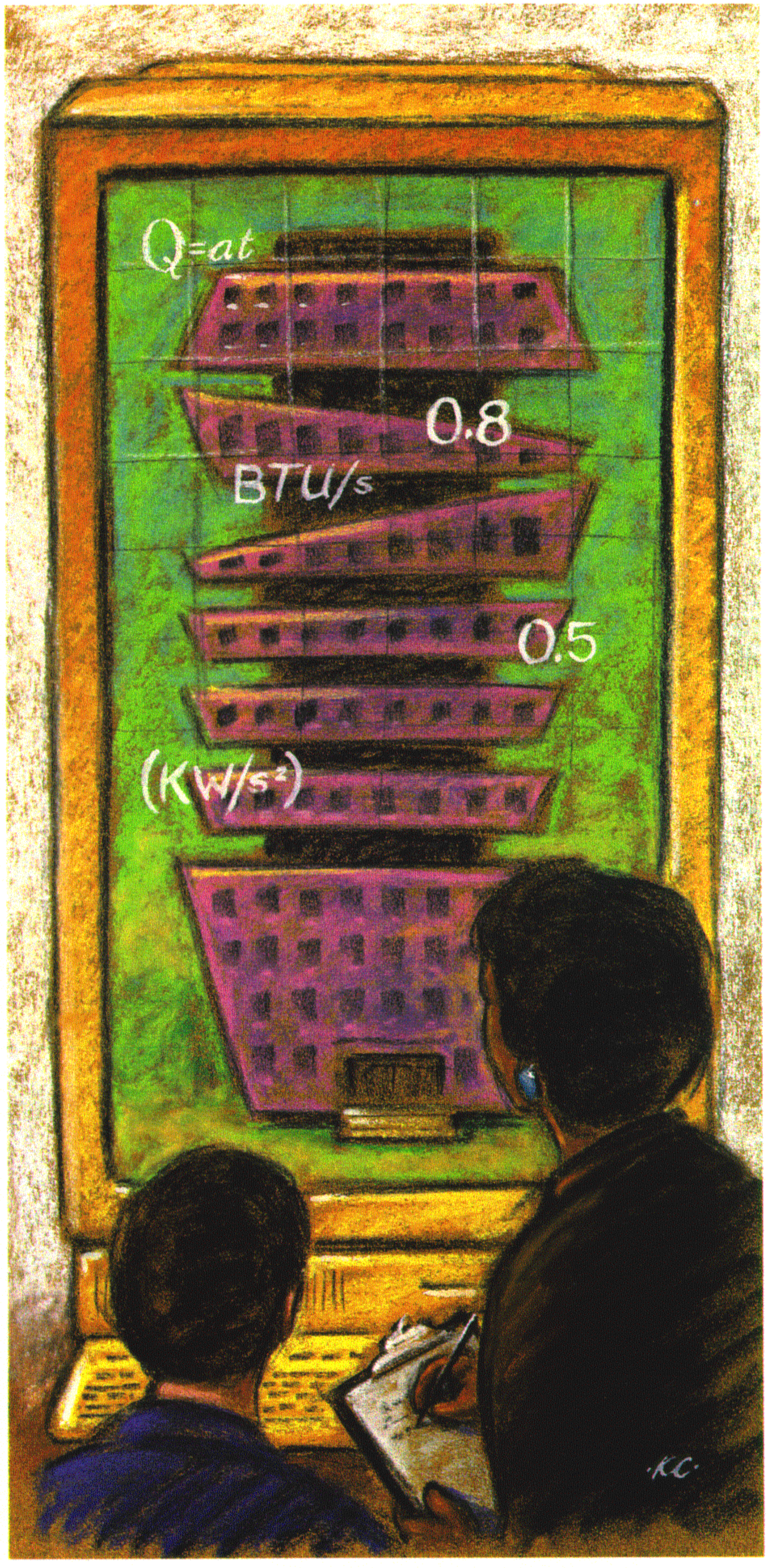
Heat transfer calculations take up a lot of computer time, so many models use a shortcut. The most common is a constant "heat-loss fraction," which the user can select.[5] The problem is that heat losses vary significantly during the course of the fire. Thus, in smaller rooms or spaces with larger surface-to-volume ratios where heat losses are significant, assuming a constant heat loss can lead to serious errors. In large, open spaces with no walls or with walls made of highly insulating materials, the constant heat-loss fraction may produce acceptable results. In most cases, however, the best approach is to use a model that calculates proper heat transfer.

Another problem can occur in tall spaces, such as atria. The major source of gas expansion and energy and mass dilution is entrainment of ambient air into the fire plume. It can be argued that, in a very tall plume, this entrainment is constrained, but most models do not allow for this. As a result, you can underestimate the temperature and smoke density and overestimate the layer volume and filling rate—the combination of which may give you inaccurate available egress times. The model CFAST implements this constraint by initially limiting the height to which the plume rises based on its buoyancy.[6]

Documentation

Only models that are rigorously documented should be allowed in any application involving legal considerations, such as code enforcement or litigation. You should not take the model developer's word that the physics is proper. The model should be supplied with a technical reference guide that includes a detailed description of the physics and chemistry included, with the proper literature references, a list of all the model's assumptions and limitations, and estimates of the accuracy of the resulting predictions based on comparisons to experimental data. Public exposure and review of the exact basis for a model's calculations, internal constants, and assumptions are necessary if it is to have credibility in a regulatory application.

While the full-source code need not be available, you will need to know the method of implementing key calculations in the code and details of the numerical solver used. This documentation



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should be freely available to any user, and a copy should be supplied with the analysis as an important supporting document.

Input data

Even if the model is correct, the results can be seriously wrong if the data you input do not represent the condition you are analyzing.

Among the most important data you can input is the source of the fire's air supply. Open doors or windows are obviously important, but so are cracks behind trim or around closed doors. Most fires, particularly large ones, quickly become ventilation-controlled, making these sources of air crucial to a correct prediction. The most frequent error that novice users of these models make is underestimating the combustion air and underpredicting the burning rate.

Other important data include the ignition characteristics of secondary fuel items and the heat transfer parameters for ceiling and wall materials. In each case, the alternative design analysis should include a list of all data values used, their source—what apparatus or test method was employed and what organization ran the test and published the data—and some discussion of the uncertainty of the data and how this might affect the conclusions.

Select the design fire

Properly specifying the fire is critical. Indeed, choosing a relevant set of design fires with which to challenge the alternative protection design is crucial to conducting a valid analysis.

The purpose of the design fire is similar to the assumed loading in a structural analysis—to tell you whether the design will perform as intended under the assumed challenge. Keeping in mind that the greatest challenge is not necessarily the largest fire, especially in a sprinklered building, it is helpful to think of the design fire in terms of its growth phase, its steady-burning phase, and its decay phase (see Figure 3).

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To realistically predict detector and sprinkler activation, the time to the start of evacuation, and the time to the occupants' initial exposure, you must select the design fire's growth rate. This is most important to egress analyses, which make up the majority of alternative design analyses.

In 1972, Gunnar Heskestad first proposed that, for these early times, the assumption that fires grow according to a power-law relation works well and is supported by experimental data.[7] He suggested fires of the form:

$$Q = \alpha t^n$$

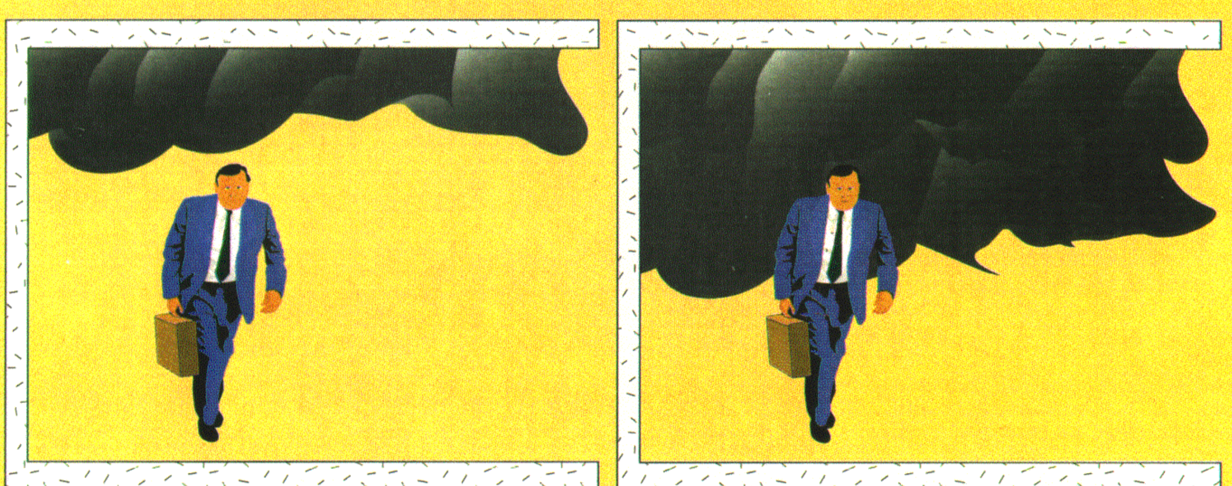
where Q is the rate of heat release (kW), α is the fire intensity coefficient (kW/s^2), t is the time in seconds, and n is 1,2,3.

Later, it was shown that, for most flaming fires, except those in flammable liquids and some others, n=2, the so-called T-squared growth rate, was an excellent representation.[8] A set of specific T-squared fires, labeled slow, medium, and fast, with fire intensity coefficients that allowed the fires to reach 1,055 kW (1,000 BTU/s) in 600, 300, and 150 seconds, respectively, were proposed for the design of fire detection systems.[9] Later, these specific growth curves, as well as a fourth called "ultrafast," which reaches 1,055 kW in 75 seconds, gained favor in general fire protection applications.[10]

This specific set of fire growth curves has been incorporated into several design methods, such as that used in NFPA 72, the *National Fire Alarm Code*, to design fire detection systems.[11] Several methods used in Australia and Japan to perform alternative design analyses also refer to them as appropriate design fires, as does a product fire risk analysis method published in the United States.[12] In the Australian methodology, the selection of the growth curve is related to the fuel load—that is, to the mass of combustible material per unit floor area.

FIGURE 1

Height of Smoke Layer



GRAPHICS: ADMASTER COMMUNICATIONS

The conservative assumption is that people are safe until the smoke layer reaches head height. In fact, people can move through smoke as long as it is cool enough and light enough to see through. Such limits on temperature and smoke density have been incorporated into some egress models and provide valid results.

However, this may not be the best approach, since the growth rate is related to the form, arrangement, and type of material, not simply to its quantity. Consider 10 kg, or 22 pounds, of wood arranged in three ways: as a solid cube, as sticks in a crib, and as a layer of sawdust. Though they represent identical fuel loads, these arrangements would have significantly different fire growth rates.

In the set of T-squared growth curves shown in Figure 4, the slow curve is appropriate for fires involving thick, solid objects, such as a solid wood table, a bedroom dresser, or a cabinet. The medium growth curve is typical of solid fuels of lower density, such as upholstered furniture and mattresses. Fast fires involve thin, combustible items, such as paper, cardboard boxes, and draperies. And ultrafast fires involve some flammable liquids, some older types of upholstered furniture and mattresses, and other highly volatile fuels.

In a highly mixed collection of fuels, selecting the medium curve is appropriate, as long as no highly flammable item is present. It should also be noted that these T-squared curves represent fire growth starting with a reasonably large, flaming ignition source. With small sources, there is an incubation period before established flaming, which can influence the response of smoke detectors, resulting in an underestimation of the time to detection. This can be simulated by adding a slow, linear growth period until the rate of heat release reaches 25 kW.

Once all the surface area of the fuel is burning, the heat release rate goes into a steady burning phase. This may be at a subflashover level, which is controlled by the fuel, or at a postflashover level, which is controlled by ventilation. The conditions in which the fire is burning should be obvious from the model output for oxygen concentration or upper-layer temperature.

Most fires will be controlled by ventilation rather than fuel, which is a distinct advantage, since it is easier to specify the sources of air than the details of the fuel. This makes the prediction insensitive to fuel characteristics and quantity because adding or reducing fuel simply makes the outside flame larger or smaller. For fires controlled by ventilation, the steady burning region can be specified at any level that results in a flame out the door, and the heat released inside the room will be controlled to the appropriate level by the model's calculation of available oxygen. For the much smaller number of fires controlled by fuel, you can find the values of heat release rate per unit area at a given radiant exposure in handbooks and use them with an estimate of the total fuel area.

Even if the model is correct, the results can be seriously wrong if the data you input do not represent the condition you are analyzing.

As the fuel is exhausted, the burning rate declines. This decline is often specified as the inverse of the growth curve, which means that fast-growth fuels decay following the inverse of the fast curve and slow-growth fuels decay following the inverse of the slow curve. It is often assumed that decay begins when only 20 percent of the original fuel is left. Although this is an assumption, it is technically reasonable.

This decay will proceed in a sprinklered occupancy as the water extinguishes the fire. A simple assumption is that the fire immediately goes out, but this is not conservative. It is better to use a recent study from the National Institute of Standards and Technology, which documents a conservative exponential diminution in burning rate when water is applied from a sprinkler.[13] Since applying water can affect a fire's combustion efficiency, you should use values of soot and gas yields that are appropriate for postflashover burning in the absence of experimental data.

Evacuation calculations

Next, you have to predict the time the building's occupants need to evacuate to a safe area and compare this to the time available from the previous steps. Whether the evacuation calculation is a hand calculation or it is done by model, it must account for several crucial factors. First, people need time to detect the fire or to be told of the fire. Next, they need time to decide what action to take. Finally, they begin to move. All of these steps take time, and time is the critical factor.

No matter how the calculation is done, all of the factors must be included in the analysis to obtain a complete picture.[14,15]

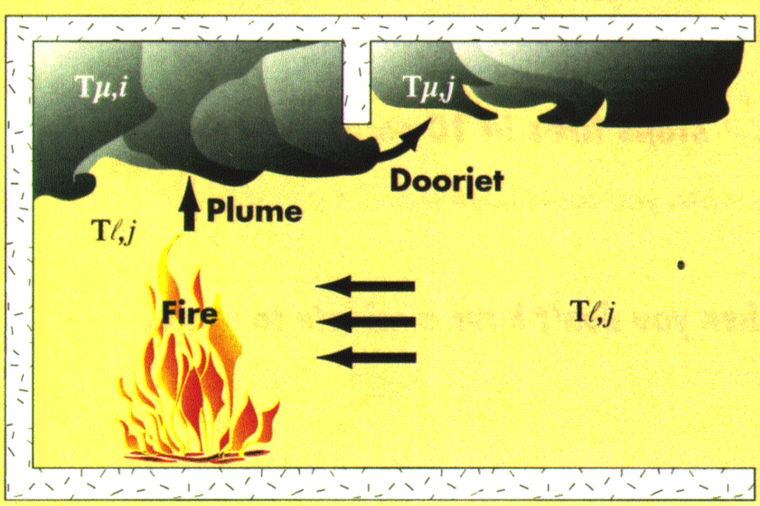
The process of emergency evacuation follows the general concepts of traffic flow. A number of models perform such calculations, and they may be more appropriate in certain occupancies than hand calculations.

Most of these models do not account for behavior and the interaction of people during the event—which is fine in most public occupancies where people don't know each other. In residential occupancies, however, family members will probably interact strongly, as will people who work together in office occupancies. The literature reports incidents in which able-bodied people helped disabled people evacuate a building, especially in office settings.[16] If such behavior is expected, it should be factored in, since it can result in significant delays in evacuation.

Models are preferred to hand calculations in situations in which large popula-

FIGURE 2

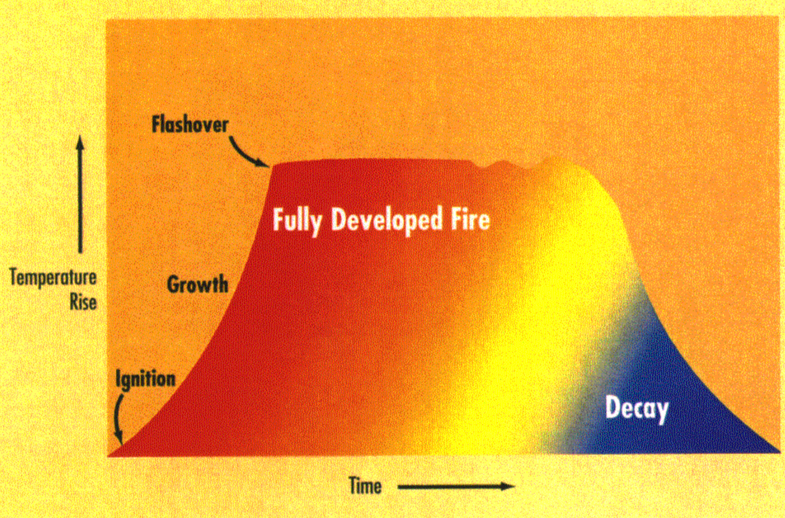
Smoke Layer Mixing at Doorway



Zone models assume that fire gases collect in layers that are internally uniform.

FIGURE 3

Growth Phases of Fire



It is helpful to think of design fires in terms of their growth, steady-burning, and decay phases.

tions are likely to congest stairways and doorways, causing the flow of people to back up—although this can be accounted for in hand calculations, as well. Crowded conditions, as well as smoke density, can cause people to walk more slowly (see Figure 5).[17] When using models, one should exercise care in choosing the path—usually the shortest—over which the model has a person traveling. Some models are optimization calculations, which give the best possible performance, and these are not acceptable for determining code equivalency.

Luckily, evacuation calculations are generally simple enough to do by hand. The most thorough presentation on this subject, and the one most often used in alternative design analysis, is that described by H. E. Nelson and H. MacLennen in the *SFPE Handbook of Fire Protection Engineering.*[18] Their procedure explicitly includes all of the factors we've already discussed and suggests how to account for each. They also deal with congestion, movement through doors and on stairs, and other related considerations.

Accounting for uncertainty

"Accounting for uncertainty" refers to dealing with the uncertainty that is inherent in any prediction. In the calculations, this uncertainty derives from the models, as well as the input data. In evacuation calculations, there is the added variability of any population of real people.

Building design and codes treat uncertainty by using safety factors. By applying enough of a safety factor, you can ensure that, if all of the uncertainty results in error in the same direction, the result is still safe.

You predict fire development and filling time so that you can select design fires that provide the worst-case scenario. Thus, a safety factor is not needed, unless the predicted result is very sensitive to the assumptions or data used. A safety factor of 2 is often recommended when performing the evacuation calculation to account for unknown variability in a given population.

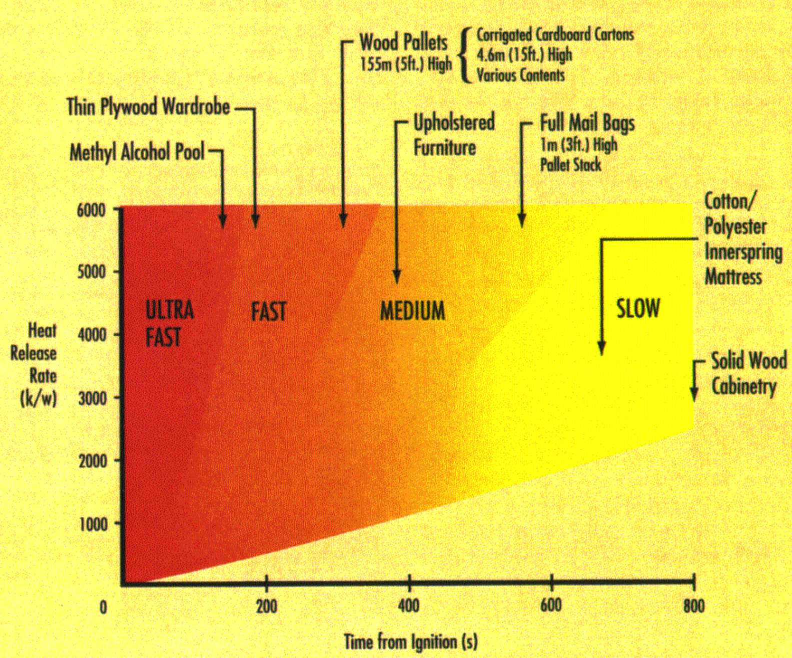
The analysis report should include a discussion of uncertainty that addresses the representativeness of the data used and the sensitivity of the results to the data and to the assumptions made. If the sensitivity is not readily apparent, you should perform a sensitivity analysis in which the data are varied to the limits to see whether the conclusions change. This is also a good point at which to justify the appropriateness of the model or the calculation method.

Reality check

The last step in any calculated analysis is the reality check. If a model or calculation produces a result that defies logic, there is probably something wrong. I've seen cases in which the model clearly produced a wrong answer—the temperature predicted approached the surface temperature of the sun—and those in which it initially looked wrong but wasn't—a dropping temperature occurred in a space next to a room with a growing fire when cold air was drawn in

FIGURE 4

T-Squared Fire Growth Curves



T-squared growth curves showing slow, medium, fast, and ultrafast fire growth curves.

through an open door. If the result is consistent with logic, sense, and experience, it's probably correct.

This is also a good time to consider whether the analysis addressed all of the important scenarios and likely events. Did it justify all the assumptions and address the uncertainties well enough to make you as comfortable as you feel when the plans review shows that all code requirements have been met?

Getting help

For a large, high-profile project, the risk of public outcry likely to occur if something goes wrong may send you in search of a higher level of confidence: You may feel compelled to obtain an independent opinion of the appropriateness of the analysis. This is reasonable.

There are qualified engineering firms in nearly every area of the country, although they will have to be paid. Indeed, the model codes allow the submitter to pay for "special studies" needed, and this could include such reviews. In addition, several universities have fire science or fire protection engineering programs whose faculty can serve as experts. Finally, experts are available at the National Institute of Standards and Technology to answer questions about the models or the data that were developed there.

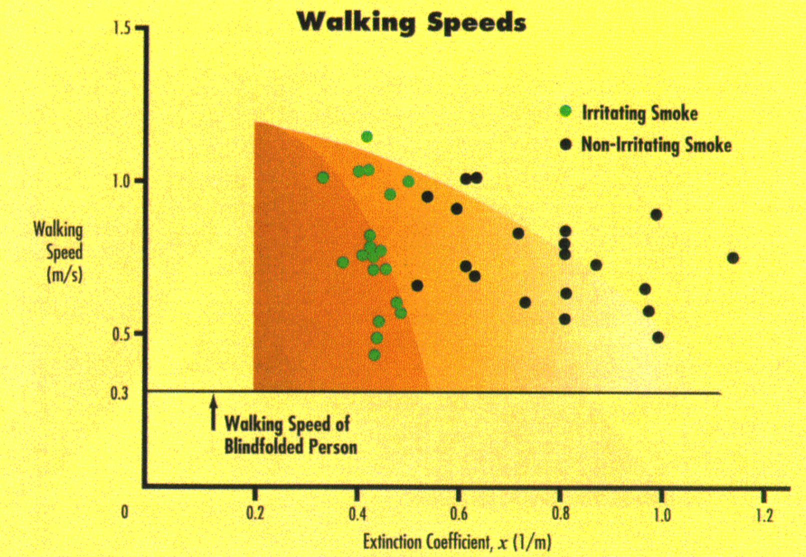
In Japan, a formal system has been put into place for this purpose. On major projects for which alternative design analyses have been performed, the local code official can consult an expert panel drawn from government and university experts, which advises the code official ultimately responsible for making the final decision.

For projects on which obtaining outside advice is not practical, the answer may lie in another approach familiar to the regulatory community—third-party certification. Criteria such as those presented here might be used to initiate a draft standard for models and calculations that are appropriate to alternative design analysis. Following a review and a consensus process, some organization might then certify or sanction specific models or methods for them, when they are used under specified conditions. This might be done through the model code process, since these codes already contain "sanctioned methods" for doing structural calculations. Such a process has already been undertaken in New Zealand, where an approved software package produces a certified report that can be submitted directly to the code official.

Alternative design calculations provide a way of achieving design flexibility and code equivalence based on performance. The advantages of such a system are widely recognized, and research is under way around the globe to formalize the process through national and international standards. Use in the United States is growing, as well.

I hope that, by applying the information presented here, code officials can become more comfortable assessing these calculations and will be able to better evaluate the alternate design process.

FIGURE 5



Walking speed decreases in dense smoke until a person moves as slowly as he would if he were blindfolded.

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1. R. Friedman, *Survey of Computer Models for Fire and Smoke*, second edition, Factory Mutual Research Corporation, Norwood, Mass., 1991.

2. P. H. Thomas, "Testing Products and Materials for Their Contribution to Flashover in Rooms," *Fire and Materials*, Volume 5, 1981, pp. 103 to 111.

3. B. J. McCaffrey, J. G. Quintiere, and M. F. Harkleroad, "Estimating Room Temperatures and the Likelihood of Flashover Using Fire Test Data Correlations," *Fire Technology*, Volume 17, 1981, pp. 98 to 119.

4. L. Y. Cooper and D. W. Stroup, *Calculating Available Safe Egress Time (ASET)—A Computer Program and Users' Guide*, NBSIR 82-2578, National Bureau of Standards, Gaithersburg, Md., 1982.

5. L. Y. Cooper and G. P. Forney, *The Consolidated Compartment Fire Model (CCFM) Comptuer Code Application CCFM.VENTS—Part 1: Physical Basis*, NISTIR 4342, National Institute of Standards and Technology, Gaithersburg, Md., 1990.

6. R. D. Peacock, G. P. Forney, P. Reneke, R. Portier, and W. W. Jones, *CFAST, The Consolidated Model of Fire Growth and Smoke Transport*, NIST Technical Note 1299, National Institute of Standards and Technology, Gaithersburg, Md., 1993.

7. G. Heskestad, *Similarity Relations for the Initial Convective Flow Generated by Fire*, FM Report 72-WA/HT-17, Factory Mutual Research Corporation, Norwood, Mass., 1972.

8. R. P. Schifiliti, "Design of Detection Systems," *SFPE Handbook of Fire Protection Engineering*, first edition, Phillip J. DiNenno, editor-in-chief, Society of Fire Protection Engineers, Boston, Mass., 1988.

9. G. Heskestad and M. A. Delichatsios, *Environments of Fire Detectors—Phase 1: Effect of Fire Size, Ceiling Height, and Material, Volume 2, Analysis*, NBS-GCR-77-95, National Bureau of Standards, Gaithersburg, Md., 1977, p. 100.

10. D. W. Stroup and D. D. Evans, "Use of Computer Models for Analyzing Thermal Detector Spacing," *Fire Safety Journal*, Volume 14, 1988, pp. 33 to 45.

11. NFPA 72, the *National Fire Alarm Code*, National Fire Protection Association, Quincy, Mass., 1993.

12. R. W. Bukowski, *A Review of International Fire Risk Prediction Methods*, paper presented at Interflam '93 Fire Safety, 6th International Fire Conference, March 30-April 1, 1993, Oxford, England, Interscience Communications, Ltd., London, England, C. A. Franks, editor, 1993, pp. 437 to 466.

13. D. Madrzykowski and R. L. Vettori, *Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System*, NISTIR 4833, National Institute of Standards and Technology, Gaithersburg, Md., 1992.

14. J. Pauls, "Movement of People," *SFPE Handbook of Fire Protection Engineering*, first edition, Phillip J. DiNenno, editor-in-chief, Society of Fire Protection Engineers, Boston, Mass., 1988.

15. J. L. Bryan, "Behavioral Response to Fire and Smoke," *SFPE Handbook of Fire Protection Engineering*, first edition, Phillip J. DiNenno, editor-in-chief, Society of Fire Protection Engineers, Boston, Mass., 1988.

16. E. Juilliet, "Evacuating People with Disabilities," *Fire Engineering*, Volume 146, Number 12, 1993.

17. T. Jin, "Visibility Through Fire Smoke," *Report of Fire Research Institute of Japan*, Volume 2, Number 33, 1971, pp. 12 to 18.

18. H. E. Nelson and H. MacLennen, "Emergency Movement," *SFPE Handbook of Fire Protection Engineering*, first edition, Phillip J. DiNenno, editor-in-chief, Society of Fire Protection Engineers, Boston, Mass., 1988.